CHROMATRON TV COLOR PROCESSING USING SEMICONDUCTOR CIRCUITS

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SUMMARY

This paper presents a simple analysis of the chrominance and luminance signals required to drive the chromatron, single-gun, color television picture tube. Conversion from the NTSC signal to the required chromatron drive is explained mathematically and graphically. Two common methods of color decoding, the 1, 2, 4 and the chroma-gate systems are described and compared. Semiconductor circuits, developed for the decoder and associated signal processing, are described.

INTRODUCTION

At present, all commercially available color TV receivers in the United States use the shadow mask picture tube with vacuum tube circuitry. The changeover to semiconductors will probably follow the present trend in black and white receivers; i.e., hybrid large-size and fully transistorized small-size sets.

Both domestic and foreign manufacturers have shown considerable interest in the small-screen color receiver. General Electric Company has announced its intention to produce a small screen portable color TV to be available in late 1965. Yaou[1] has already developed the colornet system which uses a variation of the Lawrence tube, and Sony Corporation is working on several sizes of the chromatron-type tube including a 3-gun 19-inch version.

In the United States, Paramount Pictures Corporation have developed the Chromatron tube, which was first announced in 1953.[2,3] Fairchild Semiconductor has recently designed a transistor color TV receiver using an 11-inch version of the Chromatron tube supplied by Paramount Pictures Corporation.

This paper describes the operation of the Chromatron tube and the color circuitry required in a receiver using this picture tube. Two methods of color decoding are presented: the 1, 2, 4 system[4,5] and the chroma-gate system. The 1, 2, 4 system has been developed previously with tube circuitry, but this is believed to be the first time semiconductors have been used in this system. The chroma-gate system has not been studied extensively, probably because of drift and fast-switching problems associated with tubes. These problems do not exist to the same extent when transistors are used.

CONVERSION OF THE NTSC SIGNAL TO THE CHROMATRON DRIVE SIGNALS

To understand the conversion required, one must know (a) the nature of the NTSC composite video signal obtained at the output of the receiver second detector; and (b) the picture tube construction and, hence, the signal that must be presented at the tube-control electrodes.

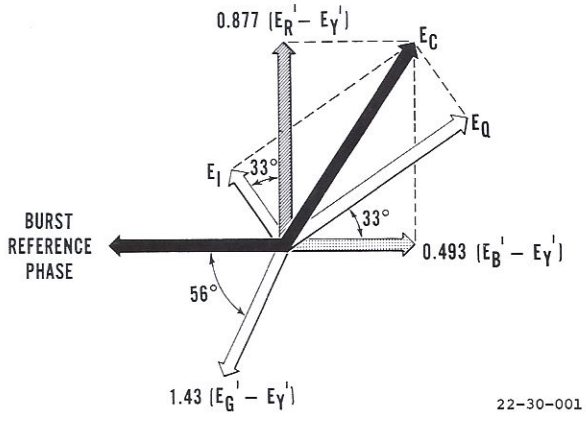

FIG. 1. N.T.S.C. demodulation characteristics for color-difference signals

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NTSC SIGNAL

The transmitted NTSC signal contains a luminance component and a chrominance component. The luminance component contains all the information necessary to produce a black and white picture. The chrominance component is a suppressed-carrier, 3.58-Mc subcarrier amplitude modulated along two phase angles in quadrature with each other (see Fig. 1). These signals are designated as E_I' and E_Q' (primed quantities indicate gamma-corrected signals) corresponding to in-phase and quadrature components. The E_I' component is modulated along an axis corresponding to orange-cyan colors, to which the eye is more sensitive, and has a bandwidth covering -1500 Kc to +500 Kc with respect to the subcarrier. The E_Q' component is modulated along an axis corresponding to green-purple colors and has a double sideband, narrow bandwidth of ±500 Kc. The color-burst reference signal is transmitted during the 'back porch' period of line blanking to give a reference phase for demodulation of the chroma signals. The NTSC composite video signal is represented as

$$E_M' = E_Y' + E_I' \cos(\omega t + 33°) + E_Q' \sin(\omega t + 33°) \qquad (1)$$

Most present-day receivers do not make full use of the wider bandwidth of the E_I' components, but restrict the bandwidth of both chroma channels to ±500 Kc. This is usually referred to as equiband operation and is chosen for reasons of economy and simplicity.

For equiband operation it is not necessary to demodulate along the E_I' and the E_Q' axes, but any other pair of quadrature axes may be used. In Fig. 1, one such pair of axes is shown corresponding to the red $E_R' - E_Y'$ and blue $E_B' - E_Y'$ color difference signals. These color difference signals can be matrixed to form the green color difference signal

$$E_G' - E_Y' = -0.51(E_R' - E_Y') - 0.19(E_B' - E_Y') \qquad (2)$$

Alternatively, $E_G' - E_Y'$ can be obtained by demodulation along a third axis shown in Fig. 1. In all cases the demodulated signals have to be multiplied by gain factors equal to the reciprocal of the values shown in Fig. 1.

THE CHROMATRON PICTURE TUBE

The construction of the Paramount Pictures' Chromatron picture tube C6003 is such that the phosphor is laid down in vertical stripes with a switching grid located close behind the phosphor as shown in Fig. 2. The tube has a standard

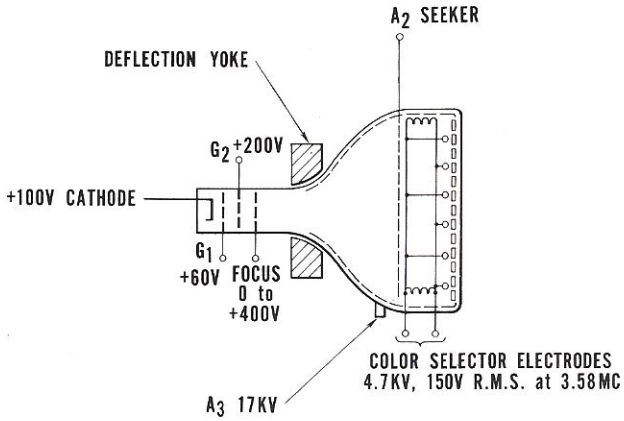

FIG. 2. The chromatron picture tube

single gun and utilizes conventional deflection coils. The phosphor stripes are in a RGRBRGRB sequence with the color-selector grids located directly behind the green and blue stripes. Alternate grid wires are connected together and brought out to a pair of terminals at the side of the tube. Tuning coils are attached inside the tube to resonate the self capacity of the color selector wires to 3.58 Mc. The color-selector terminals are driven by a 150-V RMS sinewave to provide the beam deflection required for correct color sequencing.

The phosphor stripes and color-selector grids are shown in more detail in Fig. 3(a). The stripes are about 5 mils wide with 168 stripes per inch. As shown in Fig. 3(b), applying voltages between the A and B color-selector grids will cause the beam to be deflected to strike the appropriate color stripe. The sinewave drive to the color-selector terminals gives the color sequencing shown in Fig. 3(c). The amplitude of the

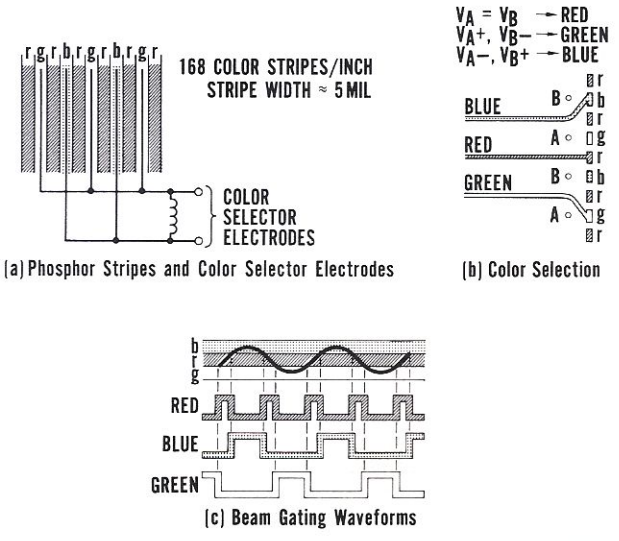

FIG. 3. Chromatron picture tube color selection

sinewave is adjusted to give equal dwell times per cycle on the three phosphors (assuming equal phosphor stripe widths and efficiencies). Under these conditions and assuming a very small spot size, the idealized sampling waveforms shown in Fig. 3(c) can be obtained. These idealized sampling waveforms represent the duration for which the appropriate red, green, or blue information is used to modulate the beam current in the tube.

COLOR PROCESSING

Figure 4 is a simplified block diagram of the required color processing. The composite video signal, after passing through a buffer stage, is split into three components: luminance, chrominance, and burst. The luminance channel filters out the lower frequency black and white component and generates sync, automatic gain control, and an amplified luminance component. The burst controls the phasing of the color-selector voltage and a 3.58-Mc reference signal, required for color demodulation. The chroma signal is separated out by a 3.58-Mc bandpass amplifier and demodulated in the chroma processing. The video amplifier drives the cathode of the picture tube with the combined luminance and processed color signals.

In both the 1, 2, 4 and chroma-gate systems described, the color, reference, luminance, and buffer blocks are identical, but the chroma processing and video amplifiers differ considerably.

The signal-processing, color-reference, and chroma-bandpass circuits are common to both the 1,2, 4 and chroma-gate systems. A detailed block diagram of these circuits is shown in Fig. 5, and the circuit schematics in Figs. 6 and 7.

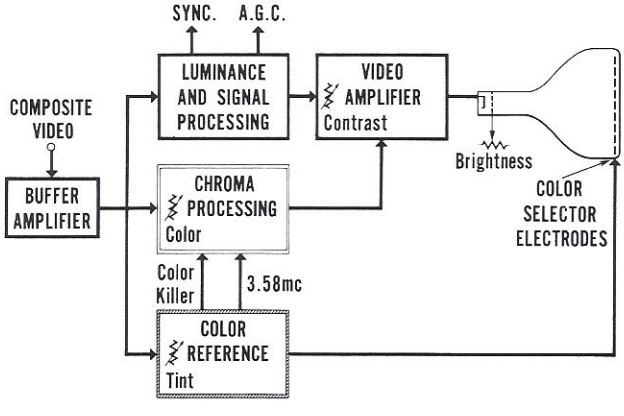

FIG. 4. Block diagram of the chromatron color processing

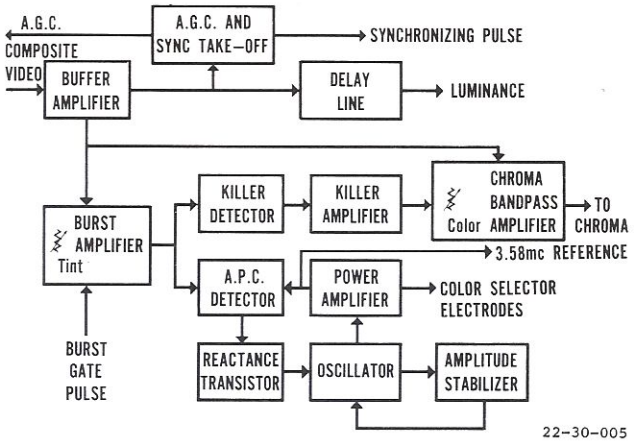

FIG. 5. Block diagram of signal processing, color reference and chroma bandpass circuits

Signal and Luminance Processing (Fig. 6)

The buffer amplifier is a direct-coupled emitter-follower (Q_1) which presents a high impedance to the second detector and provides a low-impedance source of composite video. Q_2 and Q_3, in conjunction with a keying pulse from the horizontal output transformer, provide keyed AGC. Q_4 is a transistor clamp that restores the video signal to a low DC voltage (1/2 volt) determined by the bias voltage on the base of Q_4. Q_2 and Q_4 also provide noise immunity against noise pulses during the horizontal video period. Sync take-off is accomplished by Q_5 and Q_6, using both transistors as saturated switches conducting only during sync pulse periods.

The luminance channel is band-limited by the parallel resonant circuit and by shunt rolloff prior to the 0.7-μsec delay line. The delay line introduces a 0.7-μsec delay in the luminance signal to compensate for the narrow bandwidths of the chrominance channels. The high input impedance of the emitter-follower Q_7 allows accurate termination of the delay line.

The chrominance signal is obtained by a series-resonant circuit containing the color control. The chroma amplifier, Q_9, has a double-tuned, transitionally coupled transformer in its collector. The overall bandpass of the chroma circuits is 1.4 Mc. The buffer transistor, Q_{10}, feeds the color-processing circuits. The color killer, Q_8, conducts in the absence of the color burst, cuts off Q_9, and blocks the chroma channel.

Color Reference Circuits

The functions of the color-reference circuit are as follows:

- Gate out and amplify the color-burst signal
- Phase lock a 3.58-Mc oscillator to the color burst
- Provide a color-killer voltage
- Generate the high-level 3.58-Mc sinewave required for the color-selector grids

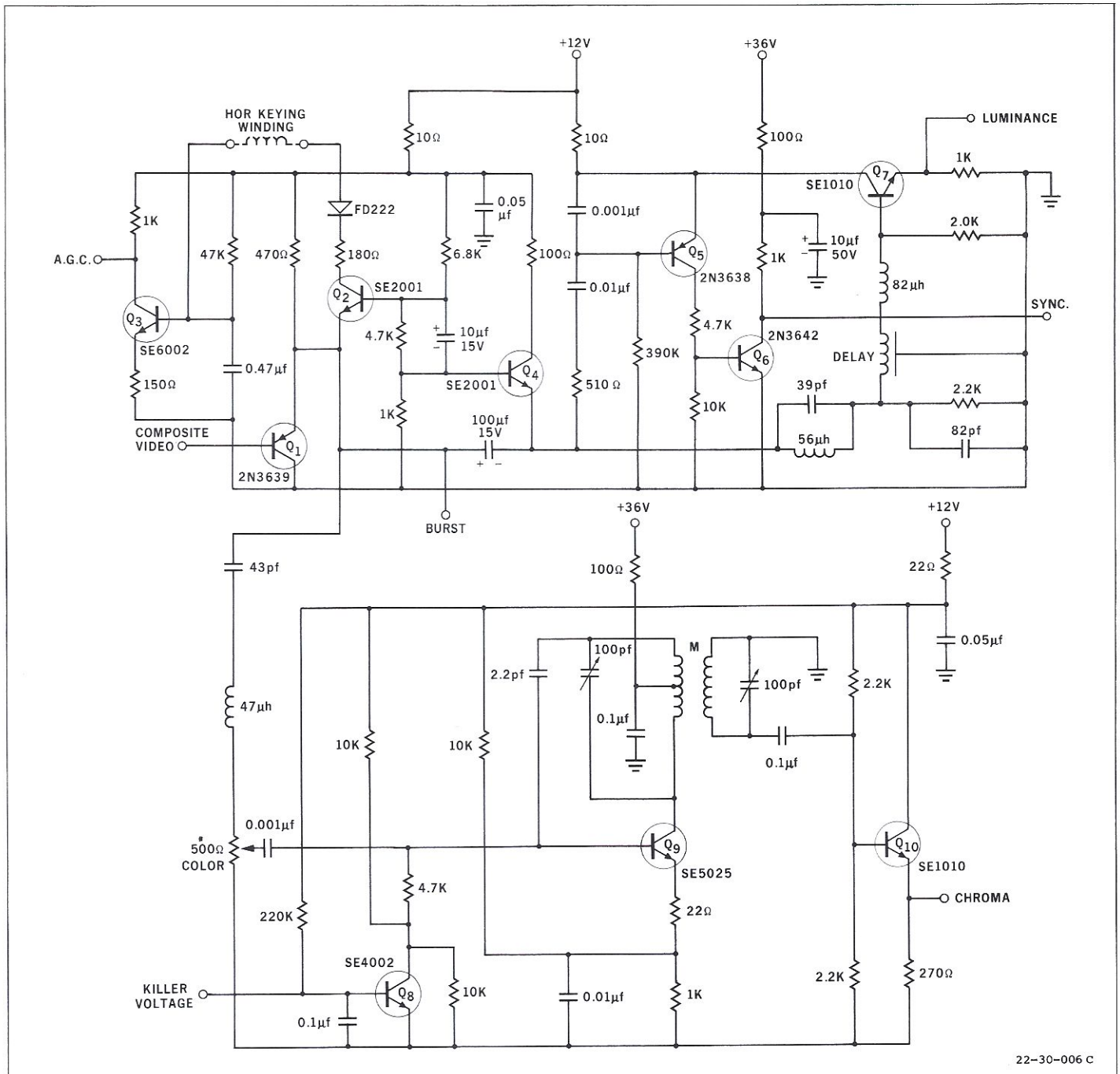

FIG. 6. Luminance signal processing and chroma amplifier

Q_{11} generates a stretched sync pulse that is used to gate the color burst. The composite video is applied to the base of Q_{12} via a phase-shifting network which contains the tint control. The burst amplifier, Q_{12}, which has a single-tuned transformer load and whose secondary is bifilar wound, drives a balanced-diode, synchronous demodulator circuit. The demodulator generates a DC voltage at the center of the two diodes proportional to the phase difference between the amplified burst and a 3.58-Mc reference signal, applied at the transformer secondary center tap. This voltage controls the operating point of the reactance transistor, Q_{13}, which series tunes the 3.58-Mc oscillator, Q_{15}. The amplitude of oscillation is stabilized by Q_{14} to ensure a constant color-selector voltage. An adjustable drive to the 3.58-Mc power amplifier is taken from the emitter of buffer stage Q_{16}.

The power amplifier, consisting of an amplifier stage (Q_{17}) driving a class 'C' push-pull output stage (Q_{18} and Q_{19}), amplifies the 3.58-Mc oscillator output to provide the 150-V RMS sinewave required by the color-selector grids. The 0° and 180° reference signals, at a level of 20-V RMS, are used to control the demodulation and remodulation in the color-processing circuits.

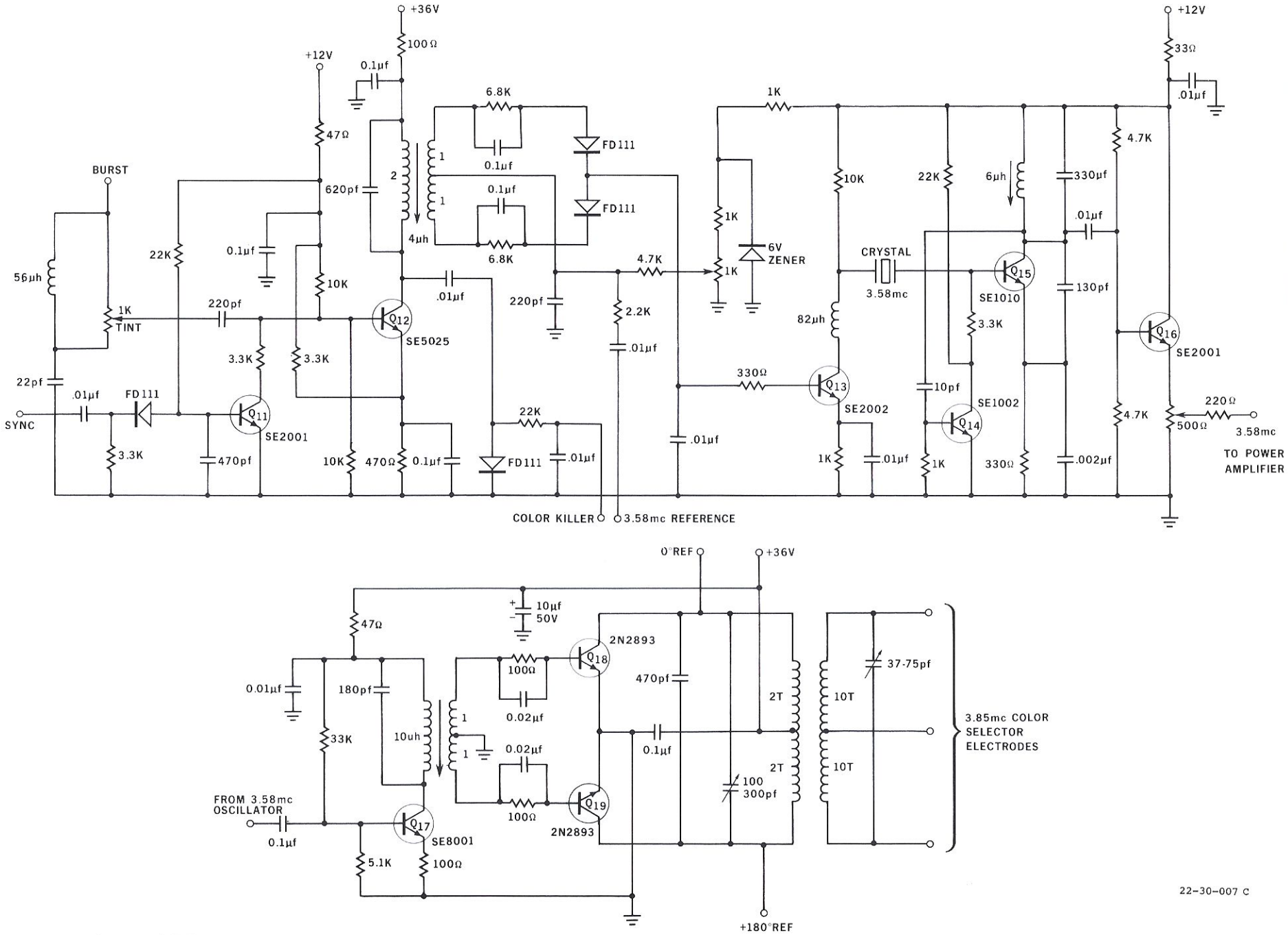

FIG. 7. Color burst – A.P.C., 3.58-mc oscillator and power amplifier

CHROMA-GATE COLOR PROCESSING

A block diagram of the Chroma-gate method of color processing is shown in Fig. 8. Chroma subcarrier information from the chroma-bandpass amplifier is demodulated along the appropriate axis shown in the NTSC phasor diagram of Fig. 1 to obtain the color difference signals, $E_R' - E_Y'$, $E_B' - E_Y'$, and $E_G' - E_Y'$. These signals are then remodulated by gated sampling as illustrated in Fig. 3(c) and added to the luminance signal to form the correct composite video to drive the Chromatron picture tube.

The chroma-gate color-processing circuitry is shown in Fig. 9. The three identical diode synchronous demodulators are conventional. $E_R' - E_Y'$, $E_B' - E_Y'$, and $E_G' - E_Y'$

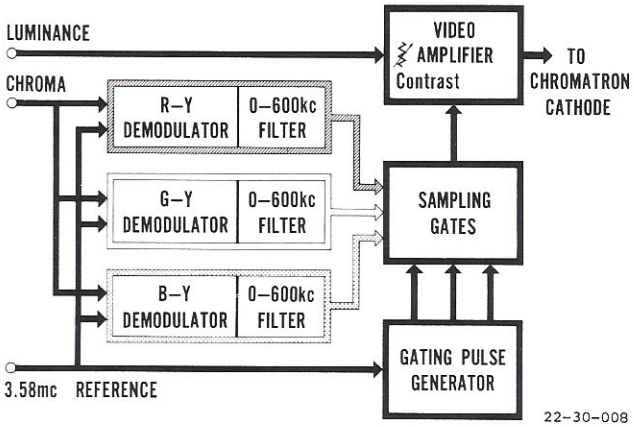

FIG. 8. Block diagram of the chroma gate color processing

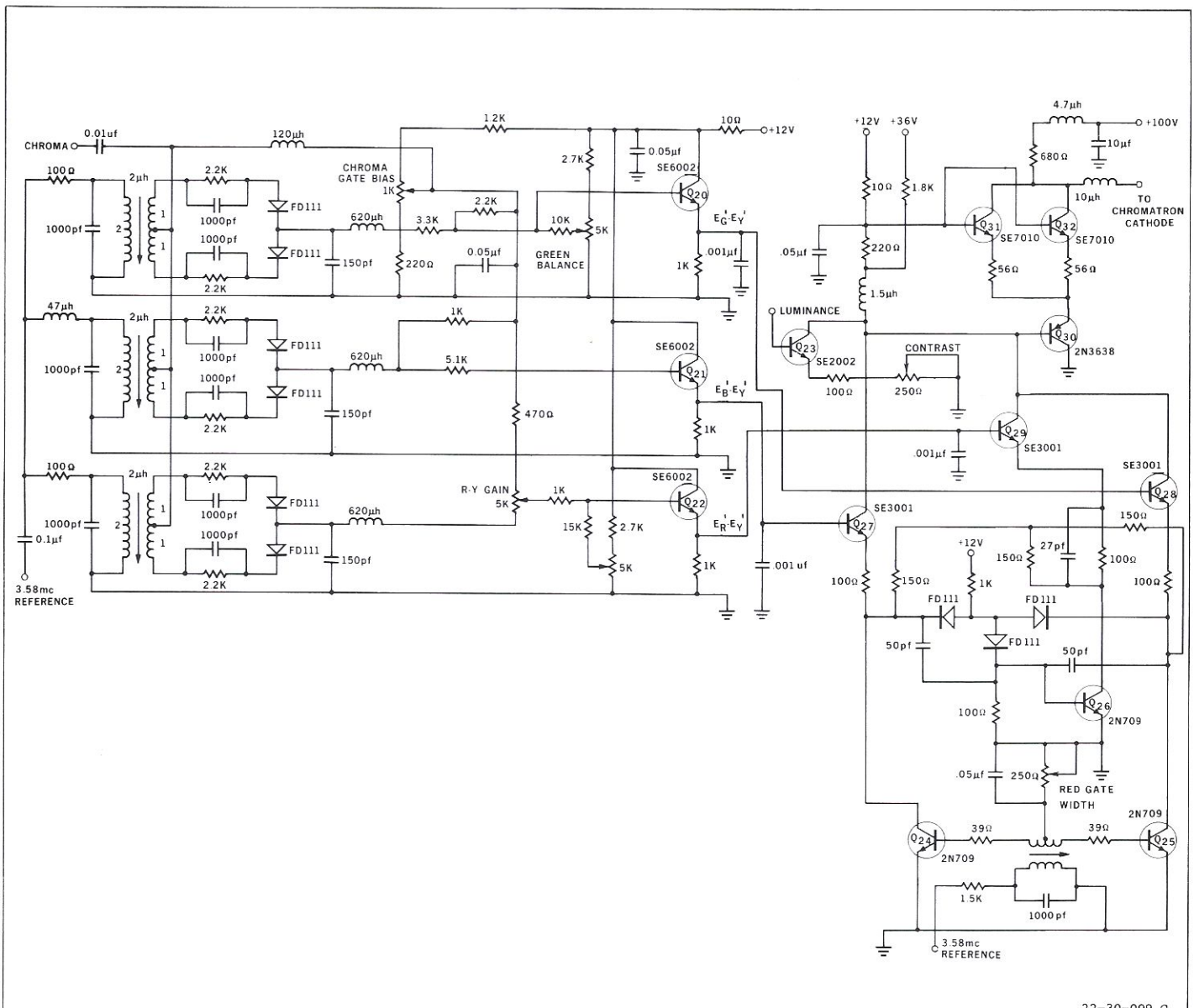

FIG. 9. Chroma gate color processing circuit

demodulation is obtained by applying the desired 3.58-Mc reference phase to each of the demodulators. The demodulator outputs are direct-coupled through low-pass filters to the buffers Q_{20}, Q_{21}, and Q_{22}, which drive the sampling circuitry. To match the NTSC color difference signals to the Chromatron drive requirements, the demodulators have the following relative gains:

$$A(E_B' - E_Y') = 1$$

$$A(E_R' - E_Y') = 0.56$$

$$A(E_G' - E_Y') = 0.34$$

The $E_R' - E_Y'$ gain is adjustable since the narrow red sampling period is affected more by the finite rise time of the gated video than the wider blue and green periods. The DC level of the color difference signals which feed the sampling circuitry is set by a bias control. Balance controls correct for slight offsets in the DC levels of the three color signals.

The three color signals are fed to the bases of the sampling transistors, Q_{27}, Q_{28}, and Q_{29}. The emitter resistors of these three transistors are switched to ground during the period that the electron beam of the picture tube passes over their respective color. The blue and green gating transistors, Q_{24} and Q_{25}, are driven from the 3.58-Mc reference signal. Drive for the red gate transistor, Q_{26}, is derived from the blue and green gates in an OR circuit. The speed-up capacitor in the emitter of the $E_R' - E_Y'$ sampling transistor, Q_{29}, compensates for the red gate time delay which results from its being derived from the blue and green gates.

Luminance is amplified in Q_{23} and added to the sampled color difference signals. The composite Chromatron video is fed to the emitter-follower, Q_{30}, which drives the parallel-connected common-base video-output transistors, Q_{31} and Q_{32}. This configuration eliminates feedback capacitance and gives the desired bandwidth capabilities. Two transistors in parallel are required since the wide bandwidth dictates a low collector load resistance and, hence, large signal currents and high power dissipation in the transistors.

1,2,4 COLOR PROCESSING

The sequence of color selection shown in Fig. 3(c) can be considered as sixth-harmonic sampling of the colors with a sequence GRB - BRG - GRB. This color sequencing is referred to as a reversed color sequence; a 1, 2, 4 color-processing scheme for a green center stripe chromatron-type tube has been described elsewhere.[5, 6]

In the 1, 2, 4 color processing scheme, amplitude-modulated components at the fundamental, second-harmonic, and fourth-harmonic frequencies of the 3.58-Mc color subcarrier are generated and combined to energize the color phosphors with the correct phases and amplitudes to give the required color. Typical waveforms to produce the desired color are shown in Fig. 10.

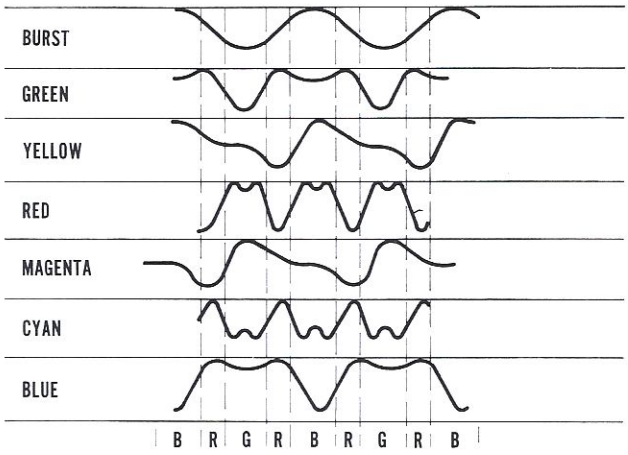

FIG. 10. Idealized 1, 2, 4 chromatron color waveforms

To explain the signal conversion for the 1, 2, 4 scheme the idealized gating waveforms must be converted to a Fourier series (Appendix A). This analysis gives

Low-frequency component (0-600 Kc)

$$E_M' = \frac{E_R'}{3} + \frac{E_G'}{3} + \frac{E_B'}{3} \qquad (3)$$

Fundamental frequency component (3.0-4.2 Mc)

$$E_1 = 0.55(E_G' - E_B') \sin \omega_o t \qquad (4)$$

Second harmonic component (6.6-7.8 Mc)

$$E_2 = -0.55\left\{E_R' - \frac{1}{2}(E_G' + E_B')\right\} \cos 2\omega_o t \qquad (5)$$

Fourth harmonic component (13.8-15 Mc)

$$E_4 = -0.275\left\{E_R' - \frac{1}{2}(E_G' + E_B')\right\} \cos 4\omega_o t \qquad (6)$$

These equations give the required signals in terms of the RGB signals. It is necessary to convert to the $E_R' - E_Y'$ and $E_B' - E_Y'$ color difference signals and then calculate the

demodulating angles and gains that are required for each signal (Appendix B). This analysis gives

$$E_M' - E_Y' = 0.19\left\{\frac{E_R' - E_Y'}{1.14}\right\} + 0.55\left\{\frac{E_B' - E_Y'}{2.03}\right\} \quad (7)$$

$$E_1 = \left[-0.32\left\{\frac{E_R' - E_Y'}{1.14}\right\} - 1.33\left\{\frac{E_B' - E_Y'}{2.03}\right\}\right] \sin \omega_o t \quad (8)$$

$$E_2 = \left[0.77\left\{\frac{E_R' - E_Y'}{1.14}\right\} - 0.45\left\{\frac{E_B' - E_Y'}{2.03}\right\}\right] \cos 2\omega_o t \quad (9)$$

$$E_4 = -\left[0.395\left\{\frac{E_R' - E_Y'}{1.14}\right\} - 0.225\left\{\frac{E_B' - E_Y'}{2.03}\right\}\right] \cos 4\omega_c t \quad (10)$$

These four signals are expressed in terms of the red and blue color difference signals obtained from the NTSC signal for equiband operation. The coefficients of

$$\frac{E_R' - E_Y'}{1.14} \quad \text{and} \quad \frac{E_B' - E_Y'}{2.03}$$

represent the gains required along these axes. The overall gain of each signal, then, is the square root of the sum of the squares of these two gains (i.e., vector addition of two vectors at right angles to each other). Similarly, demodulation angles can be found for each of these signals. These gains and angles are represented in the vector diagram of Fig. 11. The gains indicated are relative to a luminance channel gain of unity. Demodulation along these axes gives the amplitude required for the $E_M' - E_Y'$, E_1, E_2, and E_4 signals. These amplitude terms are used to remodulate $\sin \omega_o t$, $\cos 2\omega_o t$, and $\cos 4\omega_o t$ signals, respectively to give the required E_1, E_2, and E_4 components.

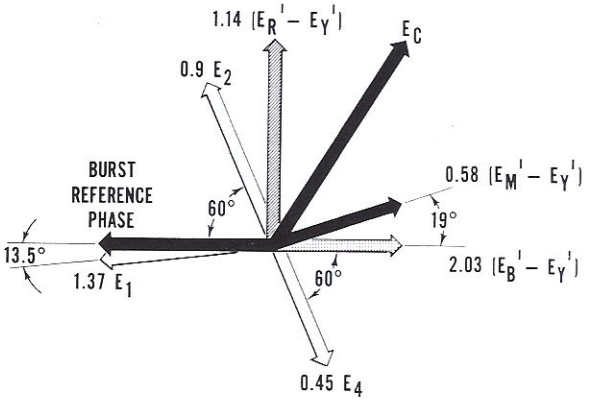

FIG. 11. 1, 2, 4 demodulation angles and gains

The demodulation angles and gains shown in Fig. 11 can also be obtained graphically by vector addition of the three primary colors E_R', E_B', and E_G', in accordance with Eqs. (3), (4), (5), and (6). In this case the vector addition must be performed on the E_R', E_B', and E_G' gain vectors required to give unity output of the three colors. The gain vectors are thus the inverse of the received amplitudes.

If the required demodulation angles and gains, together with the remodulation frequencies and phases are known it is possible to design a decoder for the 1, 2, 4 system. One way of achieving the desired result is shown in the block diagram of Fig. 12.

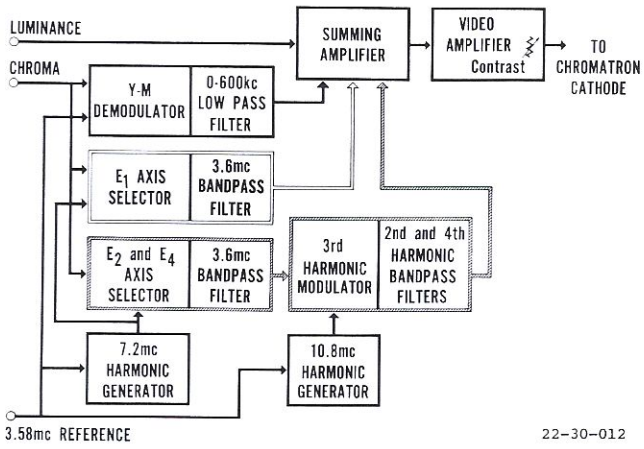

FIG. 12. Block diagram of the 1, 2, 4 color processing

The $E_Y' - E_M'$ signal is derived from a conventional synchronous diode demodulator and a 600-Kc low-pass filter. The E_1 signal is derived from narrow-angle second-harmonic sampling of the chroma signal at the required phase angle and subsequent filtering to select the required 3.58-Mc component. The E_2 and E_4 signals are similarly derived at a different demodulation angle as a 3.58-Mc component which is then converted to second- and fourth-harmonic signals in the third-harmonic modulator. The second- and third-harmonic signals must be generated in phase with the 3.58-Mc reference signal.

The second-harmonic, narrow-angle sampling is sometimes referred to as axis selection since it can be compared to the selection of a particular demodulation axis on the vector diagram (Fig. 11). All the demodulation and modulation circuits can be made identical, with the exception of differences in the sampling frequency.

The three derived chroma signals are added to the luminance signal in the summing amplifier and amplified by a wideband video amplifier to drive the Chromatron cathode.

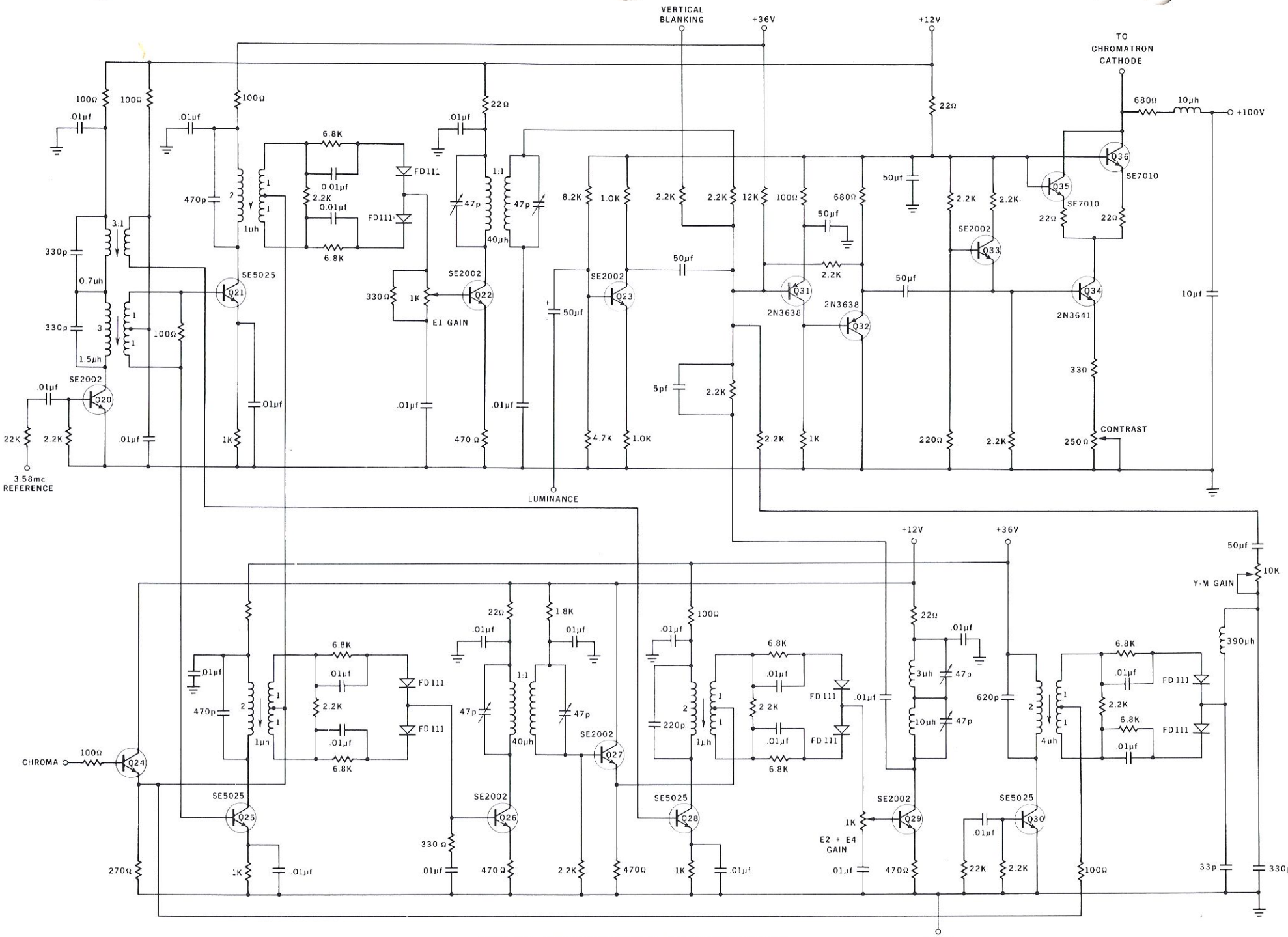

FIG. 13. Schematic of 1, 2, 4 color processing

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By using axis selectors and paying careful attention to the phase angles in both the color reference and the 1, 2, 4 color processing, it has been possible to minimize phase-shift networks. Table I gives a full list of the phase angle, and gain of the respective signals.

Table I

Signal	Demodulation Angle	Gain	Output Amplitude	Output Phase
Chroma	0°*	-	-	-
E_Y'	-	1*	1*	-
$E_M' - E_Y'$	+199°	0.58	0.33	-
E_1	+13°	1.37	1.1	+130°
E_2	+300°	0.9	1.1	+103°
E_4	+120°	0.45	0.55	+90°
Color Reference & Selector Voltage	-	-	400V p-p	+13°

*Basic Reference Units

Circuit Schematic of the 1,2,4 System

The complete circuit schematic of the 1, 2, 4 System is shown in Fig. 13. The Q_{24} buffer stage drives the synchronous demodulator. Second- and third-harmonic reference signals for the synchronous demodulators are generated by Q_{20}. Q_{21}, with its diodes, and filter stage Q_{22} generate the E_1 signal. Q_{25} and Q_{26} generate a 3.58-Mc component containing the amplitude information for the E_2 and E_4 signals. Q_{28} and filter stage, Q_{29}, generate the E_2 and E_4 signals at 7.2 Mc and 14.4 Mc respectively. Q_{30} and a low-pass filter generate the $E_Y' - E_M'$ low-frequency signal.

All demodulators operate in identical modes except for sampling frequency and phase. Second-harmonic sampling is associated with Q_{21} and Q_{25}, third-harmonic sampling with Q_{28}, and fundamental sampling with Q_{30}. The phase angles of the sampling waveforms are very important, and slight detuning of the transformers in the collectors of Q_{20}, Q_{21}, Q_{25}, Q_{28}, and Q_{30} is necessary to obtain the correct phase relationships shown in the table.

The resulting signals E_1, $E_2 + E_4$, $E_Y' - E_M'$, and the luminance signal are mixed together at the base of Q_{32} to produce the desired Chromatron drive signal. Q_{31} and Q_{32} are a wideband feedback pair providing a low input impedance so that the mixing of the four signals can be achieved with a minimum of interaction. Q_{33} restores the DC component in the final video signal. The overall bandwidth of the video amplifier is sufficient to pass the 14.4-Mc fourth-harmonic frequencies. The output configuration, which consists of the common-emitter stage, Q_{34}, and two grounded-base transistors, Q_{35} and Q_{36} connected in parallel, eliminates feedback capacitance and gives the desired bandwidth capability.

CONCLUSION

Both the chroma-gate and 1, 2, 4 color processing systems are capable of giving good picture quality with the Chromatron-type tube. A comparison of color purity indicates a slight advantage to the 1, 2, 4 system which can be attributed to the somewhat narrower angle color sampling of the picture-tube phosphors effectively obtained with this system. Circuit simplicity and ease of alignment are advantages of the chroma-gate system.

The feasibility of producing a small color TV set using the Chromatron-type tube and silicon semiconductors has been demonstrated. At present, the color-decoding circuitry required is more complicated than in a shadow mask receiver. This is offset, however, by the simple-scanning, high-voltage, and alignment circuits required by the Chromatron tube.

ACKNOWLEDGEMENTS

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APPENDIX A

FOURIER ANALYSIS OF SAMPLING PULSES

Each RGB sampling can be considered as a series of rectangular pulses as shown in Fig. 3(c). For repetitive pulses of this form the Fourier series can be written generally as

$$y = E\left[k + \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{\sin n k\pi}{n}\cos n(\omega t + \theta)\right] \qquad (A.1)$$

where θ is the angle at which the center of the pulse is displaced from a zero reference 0° and k is the fraction of the cycle occupied by the pulse.

For Red $\theta = 0$ $k = \frac{1}{3}$ $\omega = 2\omega_o$

For Green $\theta = 90°$ $k = \frac{1}{3}$ $\omega = \omega_o$

For Blue $\theta = 270°$ $k = \frac{1}{3}$ $\omega = \omega_o$

Now calculating the series for each color we have:

Red

$$y_R = E_R'\left[\frac{1}{3} + \frac{2}{\pi}\left\{\sin\frac{\pi}{3}\cos 2\omega_o t + \frac{\sin\frac{2\pi}{2}}{2}\cos 4\omega_o t\right\}\right]$$

(ignoring all harmonics above the fourth)

$$y_R = E_R'\left[\frac{1}{3} + \frac{\sqrt{3}}{\pi}\cos 2\omega_o t - \frac{\sqrt{3}}{2\pi}\cos 4\omega_o t\right] \qquad (A.2)$$

Green

$$y_G = E_G'\left[\frac{1}{3} + \frac{1}{\pi}\left\{\sin\frac{\pi}{3}\cos(\omega_o t - 90°) + \frac{\sin\frac{2\pi}{3}}{2}\cos 2(\omega_o t - 90°) + \frac{\sin\frac{3\pi}{3}}{3}\cos 3(\omega_o t - 90°)\right\}\right]$$

(ignoring all harmonics above the fourth)

$$y_G = E_G'\left[\frac{1}{3} + \frac{\sqrt{3}}{\pi}\sin\omega_o t - \frac{\sqrt{3}}{2\pi}\cos 2\omega_o t - \frac{\sqrt{3}}{4\pi}\cos 4\omega_o t\right] \qquad (A.3)$$

Blue

$$y_B = E_B'\left[\frac{1}{3} + \frac{2}{\pi}\left\{\sin\frac{\pi}{3}\cos(\omega_o t + 90°) + \frac{\sin\frac{2\pi}{3}}{2}\cos 2(\omega_o t + 90°) + \frac{\sin\frac{3\pi}{3}}{3}\cos 3(\omega_o t + 90°) + \frac{\sin\frac{4\pi}{3}}{4}\cos 4(\omega_o t + 90°)\right\}\right]$$

(ignoring all harmonics above the fourth)

$$y_B = E_B'\left[\frac{1}{3} - \frac{\sqrt{3}}{\pi}\sin\omega_o t - \frac{\sqrt{3}}{2\pi}\cos 2\omega_o t - \frac{\sqrt{3}}{4\pi}\cos 4\omega_o t\right] \qquad (A.4)$$

Adding these three signals together and collecting the harmonic terms together we obtain

(1) A low frequency component

$$E_M' = \frac{E_R'}{3} + \frac{E_G'}{3} + \frac{E_B'}{3}$$

(2) A fundamental frequency component

$$E_1 = \frac{3}{\pi}\left[E_G' - E_B'\right]\sin\omega_o t$$

(3) A second harmonic component

$$E_2 = \frac{3}{\pi}\left[E_R' - \frac{E_G'}{2} - \frac{E_B'}{2}\right]\cos 2\omega_o t$$

(4) A fourth harmonic component

$$E_4 = \frac{3}{2\pi}\left[E_R' - \frac{E_G'}{2} - \frac{E_B'}{2}\right]\cos 4\omega_o t$$

APPENDIX B

1, 2, 4, SIGNALS IN TERMS OF $E_R' - E_Y'$ AND $E_B' - E_Y'$ SIGNALS

$$E_M' = \frac{E_R'}{3} + \frac{E_G'}{3} + \frac{E_R'}{3}$$

$$\therefore E_M' - E_Y' = \frac{E_R' - E_Y'}{3} + \frac{E_G' - E_Y'}{3} + \frac{E_B' - E_Y'}{3}$$

but

$$E_G' - E_Y' = -0.51\,(E_R' - E_Y') - 0.19\,(E_G' - E_Y')$$

$$\therefore E_M' - E_Y' = \frac{0.49}{3}(E_R' - E_Y') + 0.81\,(E_B' - E_Y')$$

$$\therefore E_M' - E_Y' = 0.19\left\{\frac{E_R' - E_Y'}{1.14}\right\} + 0.55\left\{\frac{E_B' - E_Y'}{2.03}\right\} \quad \text{(B.1)}$$

$$E_1 = 0.55\,(E_G' - E_B')\sin\omega_o t$$

but

$$E_G' - E_B' = (E_G' - E_Y') - (E_B' - E_Y')$$

$$= -0.51(E_R' - E_Y') - 0.19\,(E_B' - E_Y') - (E_B' - E_Y')$$

$$= -0.51(E_R' - E_Y') - 1.19\,(E_B' - E_Y')$$

$$\therefore E_1 = \left[-0.32\left\{\frac{E_R' - E_Y'}{1.14}\right\} - 1.33\left\{\frac{E_B' - E_Y'}{2.03}\right\}\right]\sin\omega_o t \quad \text{(B.2)}$$

$$E_2 = 0.55\left[E_R' - \frac{1}{2}(E_G' + E_B')\right]\cos 2\omega_o t$$

but

$$E_R' - \frac{1}{2}(E_G' + E_B') = E_R' - E_Y' - \frac{1}{2}(E_G' - E_Y') - \frac{1}{2}(E_B' - E_Y')$$

$$= (E_R' - E_Y') + 0.255\,(E_R' - E_Y')$$

$$+ 0.95\,(E_B' - E_Y') - 0.5\,(E_B' - E_Y')$$

$$= 1.255\,(E_R' - E_Y') - 0.405\,(E_B' - E_Y')$$

$$\therefore E_2 = \left[0.79\left\{\frac{E_R' - E_Y'}{1.14}\right\} - 0.45\left\{\frac{E_B' - E_Y'}{2.03}\right\}\right]\cos 2\omega_o t \quad \text{(B.3)}$$

Similarly

$$E_4 = -\left[0.395\left\{\frac{E_R' - E_Y'}{1.14}\right\} - 0.225\left\{\frac{E_B' - E_Y'}{2.03}\right\}\right]\cos 4\omega_o t \quad \text{(B.4)}$$